

Measurement of photons via conversion pairs in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the PHENIX experiment at RHIC

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Abstract. Thermal photons can provide information on the temperature of the new state of matter created at RHIC. In the p_T region of 1–3 GeV/c thermal photons are expected to be the dominant direct photon source. Therefore, a possible excess compared to a pure decay photon signal due to a thermal photon contribution should be seen in the double ratio $(\gamma/\gamma(\pi^0))_{\text{Measured}}/(\gamma/\gamma(\pi^0))_{\text{Simulated}}$, if sufficient accuracy can be reached. We present a method to reconstruct direct photons by measuring e^+e^- -pairs from external photon conversions.

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1. Introduction

Direct photons are produced during all stages of heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC). Because they do not interact strongly, they escape the medium unaffected by final state interactions and provide a promising signature of the earliest and hottest stage of the quark-gluon plasma (QGP) [1].

On a microscopic level, the main sources of direct photons from a QGP are quark-gluon Compton scattering ($qg \rightarrow \gamma q$), quark-antiquark annihilation ($q\bar{q} \rightarrow \gamma g$) and bremsstrahlung involving thermalized partons [2]. Direct photons are also produced in initial hard scattering processes which involve the same reactions but among the incoming partons.

At RHIC energies thermal photons are predicted to be the dominant source of direct photons in a p_T window between 1–3 GeV/c [1].

Direct photons have been measured with PHENIX in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [3]. The inclusive photon spectra measured with the Electromagnetic Calorimeter (EMC) have been compared to the expected background from

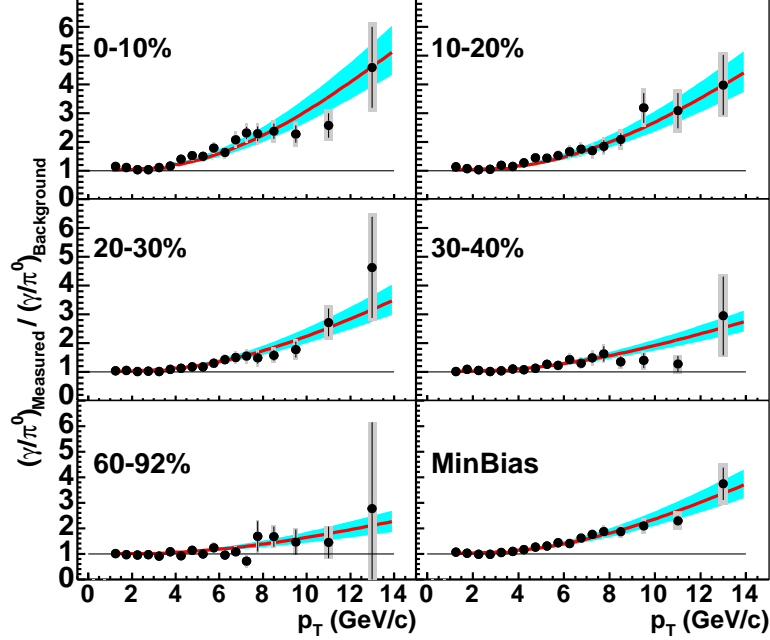


Fig. 1. Double ratio of the measured invariant yield ratio, $(\gamma/\pi^0)_{\text{Measured}}$, to the background decay ratio, $(\gamma/\pi^0)_{\text{Background}}$, as a function of p_T for minimum bias and for five centralities of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

hadronic sources, based on the measured π^0 and η spectra and a cocktail of other hadronic decays (η' , K_S^0 , ω), assuming m_T scaling.

Fig. 1 shows the double ratio of the measured invariant yield ratio to the background decay ratio as a function of p_T for minimum bias and for five centrality classes. The measurement of direct photons production at high p_T scales with the number of binary collisions in agreement with NLO perturbative QCD predictions and therefore confirms medium effects as the origin of jet suppression. In the low p_T region, where a thermal signature is expected, a significant measurement remains limited by systematic uncertainties due to the energy resolution and the photon identification with the EMC.

In order to overcome such limitations, dielectron pairs offer some advantages because of the superior momentum resolution of charged particles at low momenta and excellent identification of conversion photons; while other methods [4] try to use low mass dielectron pairs from internal conversions, the method presented here uses real photon conversions in the beam pipe.

2. Thermal photon analysis

The excellent capabilities of the PHENIX detector to measure electrons suggest to circumvent the limitations of the conventional direct photon measurement [3] at low photon energies by measuring photons via their conversion into e^+e^- -pairs. The momentum resolution ($\sim 1\%$) of the charged tracking devices proves superior to the energy resolution of the EMC ($\sim 10\%$) in the p_T region of interest (1–3 GeV/c).

To identify e^+e^- -pairs from photon conversions, a single electron identification cut is applied, which require signals from at least two phototubes in the Ring Imaging Cherenkov Detector (RICH) matching to a reconstructed charged track in the Drift Chamber (DC). No further electron identification cuts were applied since the pair cuts (see Sect. 2.1) to separate conversion photons from other e^+e^- -pairs are more efficient and powerful enough to provide a very clean photon conversion sample.

The extracted photon conversions are tagged with photons reconstructed in the EMC to determine the contribution from $\pi^0 \rightarrow \gamma\gamma$ decays (see Sect. 2.2).

All yields are measured as a function of p_T of the e^+e^- -pair, which makes a direct comparison of the inclusive photon yield, N_γ^{incl} , and the tagged photon yield, $N_\gamma^{\pi^0\text{tag}}$, possible:

$$N_\gamma^{\text{incl}}(p_T) = \epsilon_{e^+e^-} a_{e^+e^-} \gamma^{\text{incl}}(p_T) \quad (1)$$

$$N_\gamma^{\pi^0\text{tag}}(p_T) = \epsilon_{e^+e^-} a_{e^+e^-} \epsilon_\gamma(p_T) f \gamma^{\pi^0}(p_T) \quad (2)$$

The measured yield of inclusive photons depends on the reconstruction efficiency $\epsilon_{e^+e^-}$ and the PHENIX acceptance $a_{e^+e^-}$ of the conversion e^+e^- -pair. The tagged photon yield depends in addition on the efficiency to reconstruct the second photon in the EMC $\epsilon_\gamma(p_T)$ and on the conditional probability f to find it in the EMC acceptance, given that the e^+e^- -pair has been reconstructed already. Here, $\epsilon_\gamma(p_T)$ is weighted with the p_T distribution of the e^+e^- -pair. In the ratio $N_\gamma^{\text{incl}}/N_\gamma^{\pi^0\text{tag}}$ the e^+e^- -pair reconstruction efficiency and acceptance correction factor cancel.

A ratio of the hadronic decay photon yield, N_γ^{hadr} , and the tagged photon yield from π^0 decays, $N_\gamma^{\pi^0\text{tag}}$, is calculated with simulations.

$$N_\gamma^{\pi^0\text{tag}}(p_T) = f N_\gamma^{\pi^0}(p_T) \quad (3)$$

The comparison of the ratio in data and in simulations in a double ratio leads to an expression that is equivalent to the ratio of inclusive and decay photons as shown in Eq. (4).

$$\frac{\gamma^{\text{incl}}(p_T)}{\gamma^{\text{hadr}}(p_T)} = \frac{\epsilon_\gamma(p_T) \cdot \left(\frac{N_\gamma^{\text{incl}}(p_T)}{N_\gamma^{\pi^0\text{tag}}(p_T)} \right)_{\text{Data}}}{\left(\frac{N_\gamma^{\text{hadr}}(p_T)}{f N_\gamma^{\pi^0}(p_T)} \right)_{\text{Sim}}} \quad (4)$$

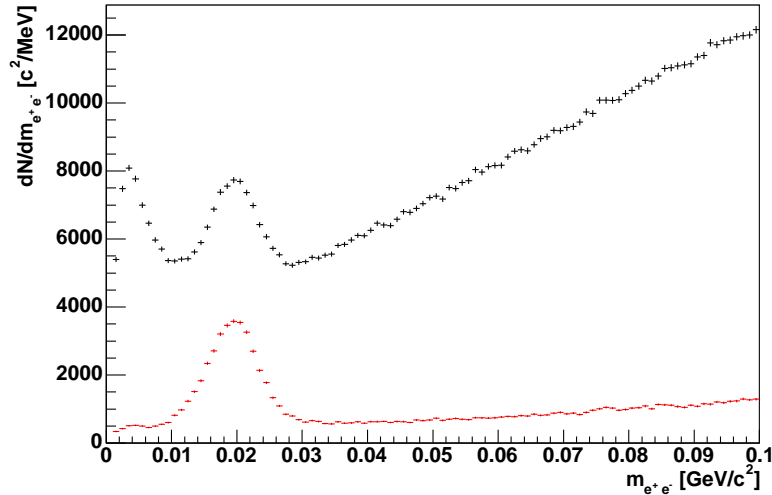


Fig. 2. Invariant mass of e^+e^- -pairs before (black) and after (red) applying cuts on the orientation of the e^+e^- -pair in the magnetic field.

The only remaining factors are the reconstruction efficiency of the photon in the EMC, $\epsilon_\gamma(p_T)$, and the conditional acceptance f in the simulation part of the double ratio, which have both been determined with Monte Carlo simulations (see Sect. 2.3).

2.1. Photon Conversions

Since the PHENIX tracking algorithm assumes the track to originate from the collision vertex, off-vertex conversion pairs are reconstructed with an artificial opening angle which leads to an invariant mass that is proportional to the radius at which the conversion occurs.

Therefore, photon conversions that occur in the beam pipe material (Be, 0.3% radiation length) at a radius of 4 cm are reconstructed with an invariant mass of $\sim 20 \text{ MeV}/c^2$. Fig. 2 shows an invariant mass spectrum of e^+e^- -pairs in the range 0–0.1 GeV/c^2 . The peak from photon conversions in the beam pipe at $20 \text{ MeV}/c^2$ can be clearly separated from Dalitz decays $\pi^0 \rightarrow \gamma e^+e^-$, which dominate the spectrum below $10 \text{ MeV}/c^2$, and combinatorial background pairs, whose contribution increases toward higher invariant masses.

The photon conversion pairs, which have no intrinsic opening angle, can be distinguished from Dalitz decays and purely combinatorial pairs by cutting on the orientation of the e^+e^- -pair in the magnetic field.

Fig. 2 shows the invariant mass spectra of e^+e^- -pairs before (black) and af-

ter (red) applying these pair cuts. The yield from integrating the mass region $< 35 \text{ MeV}/c^2$ of the conversion peak is corrected for the remaining p_T dependent contamination of $\sim 15.0 \pm 2.0$ (syst) % due to combinatorial e^+e^- -pairs which has been determined with mixed events.

2.2. Tagging of Decay Photons

To reveal which of these conversion photons come from $\pi^0 \rightarrow \gamma\gamma$ decays, the e^+e^- -pairs in the conversion peak are combined with photons which have been measured in the EMC, under loose cuts based on the time of flight and the shower profile for photons with a minimum p_T of 0.3 GeV/c, and their invariant mass is calculated (see Fig. 3).

The reconstruction efficiency $\epsilon_\gamma(p_T)$ of the loose photon has been estimated with a full GEANT simulation which embed simulated photons into real EMC data, therefore providing a combined information on the photon identification efficiency and occupancy effects. The overall efficiency is determined to be 82 ± 1 % independent of p_T beyond the minimum p_T cut off.

Conversion photons that are identified as decay products of π^0 can be tagged as $N_\gamma^{\pi^0 \text{ tag}}$. This signal has a large combinatorial background due to the high photon multiplicity in Au + Au collisions.

The combinatorial background is reproduced with an event mixing method, which creates uncorrelated pairs of photons and e^+e^- -pairs from different events. The mixed event spectrum is normalized to the same event spectrum well outside the π^0 mass region (0–100 MeV/c², 170–250 MeV/c²) and subtracted.

The statistical error on the normalization factor is on the order of 0.2 % and depends only on the statistics in the same event spectrum in the normalization region. As an example, the resulting π^0 signal for e^+e^- -pairs with $0.8 < p_T \leq 1.2 \text{ GeV}/c$ is shown as insert in Fig. 3.

Mean and σ are determined by a fit of the background subtracted data with a Gaussian. The data are also fitted to the sum of a second order polynomial and a Gaussian, to take into account the possibility that the shape is not completely described by the mixed event spectrum. The difference in the resulting mean and σ is negligible. The mean and σ obtained by the fit are then used to integrate the data in a region $\pm 1.5 \sigma$ around the mean, chosen to optimize the signal to background ratio.

The statistical error on the extracted π^0 signal is given by:

$$\sigma_S^2 = \sum_i FG(i) + \alpha \sum_i BG'(i) + \left(\frac{\sigma_\alpha}{\alpha} \sum_i BG'(i) \right)^2 \quad (5)$$

With $FG(i)$ and $BG'(i)$ being the yields in bin i of invariant mass spectrum in same events and normalized mixed events, respectively, the summations are performed over the integration region. It is important to note that the last term in Eq. (5), is the square of the sum over the normalized background, and therefore, depends

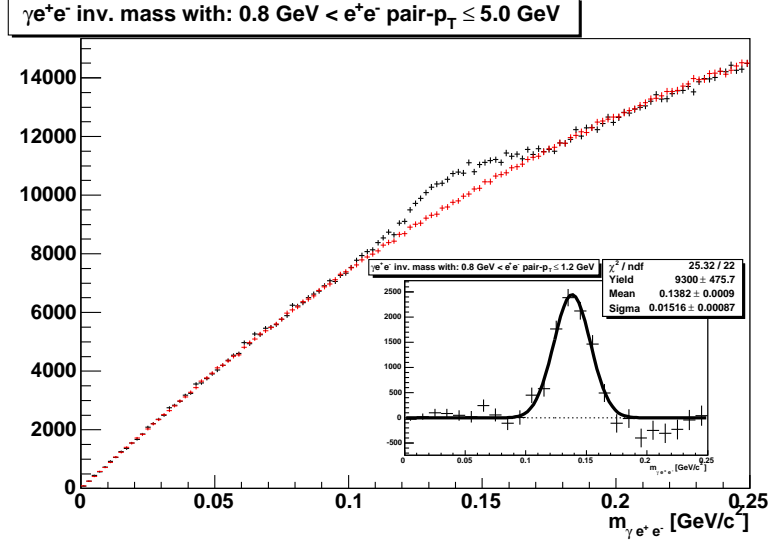


Fig. 3. Invariant mass of $\gamma e^+ e^-$ -triplets in same events (black) and normalized mixed events (red) for $e^+ e^-$ -pairs with $0.8 < p_T \leq 5.0$ GeV/c. The insert shows the invariant mass of $\gamma e^+ e^-$ -triplets after background subtraction for $e^+ e^-$ -pairs with $0.8 < p_T \leq 1.2$ GeV/c. A fit with a Gaussian is drawn and the resulting parameters shown in the box in the upper right of the graph.

on the integration region and is not bin independent. Different integration regions have been used. Variations in the resulting yield have been used to set a systematic uncertainty on the yield extraction of 2.5 % independent of p_T .

The loss of $N_{\gamma}^{\pi^0 \text{ tag}}$ due to the external conversion of the second photon is corrected by a factor $1 - p_{\text{conv}} = 94 \pm 2\%$. In this factor p_{conv} is the conversion probability due to the material budget between the vertex and the Pad Chamber 3 (PC3) in front of the EMC.

2.3. Simulations

The contribution of hadronic decays has been determined with a fast Monte Carlo simulation of π^0 and η Dalitz decays. A parameterization of the π^0 spectrum measured by PHENIX [5] has been used as input. The η distribution has been generated assuming m_T scaling ($p_T \rightarrow \sqrt{p_T^2 + m_\eta^2 - m_{\pi^0}^2}$) of the π^0 spectral shape and a normalization at high p_T to $\eta/\pi^0 = 0.45 \pm 0.04$, according to PHENIX data [6, 7]. The relative error of 9 % on the η/π^0 ratio is reduced by the branching ratio of the two photon decay and results in a 3 % error in the ratio $N_{\gamma}^{\text{hadr}}/N_{\gamma}^{\pi^0}$.

The contamination due to neutral Kaons which decay before the beam pipe has

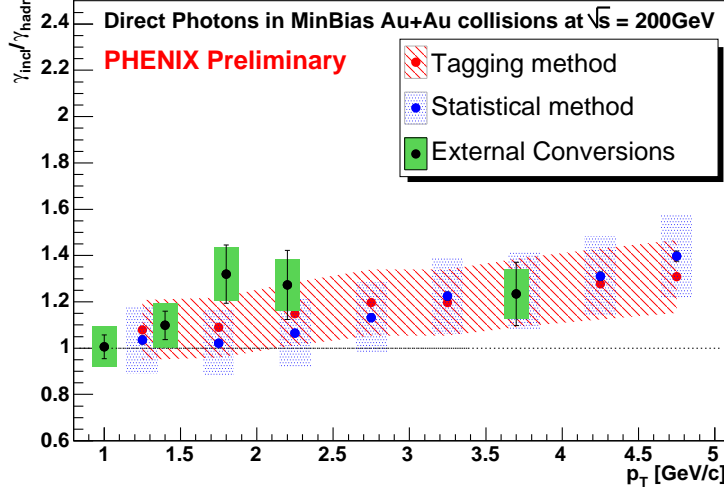


Fig. 4. Ratio of inclusive photons to decay photons, $\gamma^{\text{incl}}(p_T)/\gamma^{\text{hadr}}(p_T)$, in Minimum Bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, for three different methods.

been found negligible ($\sim 1\%$) and has been folded into the systematic error on the simulations.

The conditional probability f that the photon is reconstructed in the EMC once the e^+e^- -pair is reconstructed already was calculated with a fast Monte Carlo simulation of $\pi^0 \rightarrow \gamma e^+e^-$. The use of Dalitz decays is justified by the fact that the p_T spectra of photons from $\pi^0 \rightarrow \gamma\gamma$ are essentially identical to the e^+e^- -pair p_T spectrum from $\pi^0 \rightarrow \gamma e^+e^-$.

After the e^+e^- -pair has been filtered in the detector acceptance, the conditional acceptance f for the second photon has been calculated taking dead areas of the detector into account. Uncertainties in calculating f are found to be 5%, which is the largest source of systematic errors. The limited energy resolution of the EMC of $\sigma_E/E = 5\% \oplus 9\%/\sqrt{E}$ introduced an additional systematic error of $\sim 1\%$ due to the p_T cut at 0.3 GeV/c.

3. Conclusions

Fig. 4 shows a preliminary result for the double ratio $\gamma^{\text{incl}}(p_T)/\gamma^{\text{hadr}}(p_T)$ as in Eq. 4 for Minimum Bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The main sources of systematic errors arise from the uncertainties in the description of the detector active areas, in the peak extraction and in the assumptions of the π^0 shape and give a final systematic error on the double ratio of $\sim 7\%$.

The result of the presented analysis is compared to two other direct photon measurements in PHENIX. The first one [8] is based on the same tagging method, but instead of photons coming from conversions in the beam pipe, the clean photon sample is determined by selecting EMC clusters with very strict photon identification cuts. The second one is the ratio obtained from the statistical subtraction of measured π^0 p_T spectra from the measured inclusive photons [9].

All three analyses indicate an excess due to direct photons above the decay photon spectrum in the p_T region 1–3 GeV/c. Despite of the statistical limitations due to the low conversion probability of 0.2 % this analysis offers a smaller systematic error with respect to the conventional methods, and therefore, the intriguing ability to extend the extraction of a significant direct photon yield to low p_T .

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